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End-to-end approach to flexible and sustainable commercial spaceflight initiatives: evaluation of operational scenarios, safety aspects, spaceports and associated economic elements

F.Santoro[a]*, A. Del Bianco[b], V. Albino[c], N.Viola[d] , R.Fusaro[e]

[a] *ALTEC S.p.A., Torino, Italy, francesco.santoro@altecspace.it*
[a] *ALTEC S.p.A., Torino, Italy, alberto.delbianco@altecspace.it*
[c] *Politecnico di Bari, Bari, Italy,vito.albino@poliba.it*
[d] *Politecnico di Torino, Torino, Italy, nicole.viola@polito.it*
[e] *Politecnico di Torino, Torino, Italy, roberta.fusaro@polito.it*
* Corresponding Author

Abstract

Multiple initiatives are going on today, aimed at developing new technologies for commercial exploitation of space. The potential benefits of widening up the access to space to a broader users community affect different applications ranging from space tourism to microgravity experimentation to astronauts and pilots training; moreover, in the new space economy users communities may include parties that do not traditionally operate in the space business but can take advantage of microgravity exploitation as an opportunity to carry out experimental activities with potential more significant outcome. The present paper initially approaches commercial access to space by evaluating different mission concepts, technologies and platforms such as suborbital spaceflight, orbital spaceflight, air launch and deployment of small satellites. In order to select the most promising alternative, trade off methodologies, making use of safety, cost and complexity as figures of merit are suggested for the specific case of the suborbital flight. Moreover, the paper describes the outcome of simplified mission simulations, encompassing both suborbital vehicle as well as satellite air launch trajectories predictions. The trajectories simulations can also provide useful inputs to the vehicle design and performance analysis and are instrumental to planning air space operations after lift off from the launch site, as well as to assess logistics and operational aspects. Thus, simulations of really operating environment provide the link to the Spaceport selection process aiming at defining an adequate operating base and a set of proper ground infrastructures that efficiently support in integrated fashion the execution of the planned activities with the selected platforms. An integrated end to end approach is also described, that basing upon the specific users' needs identifies the appropriate platform and delivers the associated service matching the relevant goals. The paper finally discusses some economic and organizational aspects for developing a sustainable commercial spaceflight initiative. Ideas for next activities are drawn too, mainly focusing on trajectory validation simulation with real data coming from the initial test campaigns.

Keywords: (commercial, space, microgravity, technologies, simulations, spaceport)

Acronyms/Abbreviations

Aeroporti di Puglia S.p.A.	ADP
American Institure of Aeronautics and Astronautics	AIAA
Italian Space Agency	ASI
Air Traffic Control:	ATC
Air Traffic Management	ATM
Defence Advanced Research Project Agency	DARPA
German Aerospace Center	DLR
Distretto Tecnologico Aerospaziale	DTA
European Aviation Safety Agency	EASA
Ente Nazionale per l'Aviazione Civile:	ENAC
Ente Nazionale Assistenza al Volo	ENAV
Emergency Response Plans:	ERP
Federal Aviation Administration/Space Transportation Office:	FAA/AST
Figure of Merit	FoM
High Altitide Lighter Than Air	HALTA
International Civil Aviation Organization	ICAO
International Space Station	ISS
International Traffic in Arms Regulations	ITAR
International Telecommunication Union´s	ITU
Intermediate Experimental Vehicle	IXV
Low Earth Orbit	LEO
Liquid Oxygen	LOX
Medium Earth Orbit	MEO
Military Operating Area	MOA
New Mexico Spaceport Authority	NMSA
National Transportation Safety Board	NTSB
Operations Services	O/S
Reusable Launch Vehicles	RLV
Synergistic Air - Breathing Rocket Engine	SABRE

Safety Management Systems:	SMS
Short Takeoff and Landing	SRL
Sierra Nevada Corporation	SLC
Suborbital Reusable Vehicle	SRV
Single Stage to Orbit	SSTO
Technology Readiness Level	TRL
Telemetry and Telecommand	TT&C
United Space Alliance	ULA
Visual Flight Rules	VFR
Vertical takeoff and landing	VTOL

1. Introduction

In the recent years the commercial exploitation of space is significantly emerging through a breed of several initiatives aimed at considering space as a significant proving ground for a variety of applications, like testing new technologies, carrying out microgravity experimentation, providing flight opportunities to space tourists, and offering flexible access to space through different platforms [1]. Objective of the present paper is to address the most important ways to allow commercial access to space, describe their main characteristics and applications and match them to the relevant Spaceports characteristics and associated Ground Infrastructures.

Specific examples will also be provided on initial business plan elements characterization to verify the commercial viability of specific ground infrastructures in a new growing market. A very significant example is Spaceport America [2], the commercial operations base of Virgin Galactic, designed, built and operated by the NMSA; Spaceport America is the world's first purpose-built, commercial spaceport, intended to be the launch base of the global commercial spaceflight industry. Spaceport America is currently experiencing the relocation of specific Virgin Galactic workforce, flight and ground segment from the Mojave Spaceport [3] in preparation to start commercial operations.With Space Shuttle retirement in 2011, worldwide aerospace industry focused on new technologies aimed at developing innovative reusable Space Vehicles with the purpose of reaching the Karman line of 100 Km altitude and eventually prepare for the future generation transportation between different points on the Earth [4]. Section 2 is a survey of different mission concepts, technologies and platforms for commercial access to space [5], such as suborbital spaceflight, orbital spaceflight; HAPS stratospheric platforms are also addressed, that provide a suite of integrated services for both commercial and scientific applications in the high atmosphere. Section 3 describes some highlights on the methodology to perform tradeoff of different missions starting from a mission statement related to suborbital flights, based of the evaluation of properly identified Figures of Merit such as Safety, Cost and Complexity [6]. Section 4 provides the basic assumptions of a mathematical model approach to simulate trajectory [7] of a suborbital spaceflight system like the Virgin Galactic and identifies two different kind of missions related to both space tourism and microgravity experimentation. Section 5 decribes the main elements associated with the Ground Segment [8] to properly support the relevant mission and focuses on specific elements like Ground Stations that are flexible enough to support different kinds of commercial missions. The Ground Station can be an entry point to Countries that are willing to enter the space business and be part of both the main commercial and institutional programs. Section 6 describes specific economic and organizational aspects [21] associated to the commercial viability of outfitting specific infrastructures and services and can be used as an initial guideline to develop most complex economical and commercial approaches useful to achieve adequate fundings to develop initial capabilities of space exploitation.

2. Technologies for Commercial access to space

2.1 Virgin Galactic

The ultimate purpose of this vehicle is to carry space tourist in a sub-orbital trajectory, in order to make them appreciate some minutes in microgravity, floating in the cabin. Alternately another concept of operation is to install a scientific payload, carrying a Payload Specialist able to execute scheduled experiments. Figure 1 shows the typical Virgin Galactic Spaceflight system flight profile [9], [10].

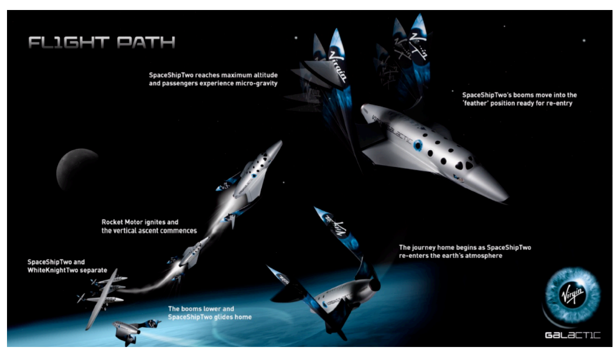

Figure 1: The Virgin Galactic SpaceShipTwo flight profile [Credits: Virgin Galactic]

The current Virgin Spaceplane is expected to accomplish only suborbital flights (not reaching LEO), landing at departure spaceport.

Take off is carried out by a Carrier called WhiteKnight to whom the SpaceShip is anchored on the bottom side (air-launch captive on bottom). This carrier is a particular aircraft with 2 fuselages, powered by 4 turbojets, able to carry the SpaceShip up to 15200 m.

Once arrived at this altitude the Ship is undocked from the Carrier and, after a certain delay, ignites its

Hybrid rocket propeller. This is the climbing phase in which the Ship increases its pitch angle up to 90 degrees, for an almost verticalascent. The ignition lasts approximately 60 seconds, followed by a coast phase, at the end of which it has to reach 100 km of altitude, the conventional boundary between atmosphere and space.

After some minutes in microgravity the Ship assumes a particular attitude configuration, called feathered, which consists in lifting aerodynamic tail surfaces to create an increase in drag in order to let a rapid descent. Once reached an altitude of 70000 ft the initial attitude is restored, letting the Spaceplane to glide to get to the spaceport on a usual landing on a runway.

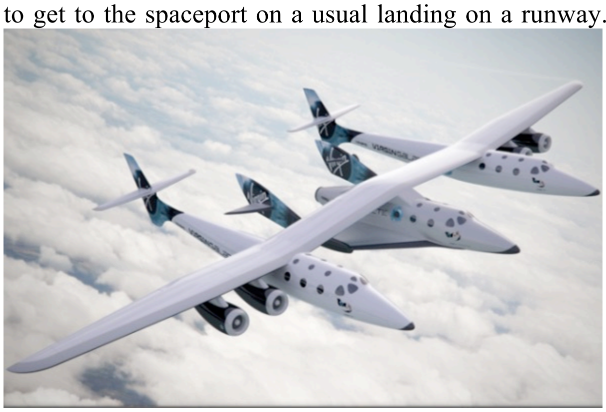

Figure 2 Shows the WhiteKnight2 and SpaceShip2 captive configuration at takeoff and flight to release altitude.

Figure 2: SpaceShip with its Carrier WhiteKnight, take off configuration [Credits: Virgin Galactic]

2.2 Blue Origin (reference to website)

Blue Origin is the only Virgin Galactic competitor in suborbital flight market with a mission profile reaching the maximum altitude slightly above the 100 Km Karman Line as shown in Figure 3. It is based on the Blue Shepard [11], a new suborbital rocket system. The system offers accommodations for payloads both inside the cabin or with direct exposure to the space environment. With about 3 minutes of high-quality microgravity, the cabin is ideal for microgravity physics, gravitational biology, technology demonstrations, and educational programs. Payloads adjacent to the largest windows in space or mounted on the outside of the vehicle can perform Earth, atmospheric, and space science research.

The system is ideal to launch experiments multiple times to iterate on findings, improve statistics, or rapidly collect data. As human flights begin, it will also be possible to fly payloads for hands-on experimentation.

Inside the cabin, the system can readily accommodate experiments from small NanoLabs up to 100 kg (225 lb). These payloads are supported by unique avionics system and software, including:

- Robust control systems
- Scientific Cameras
- Data storage
- Electrical power
- Vehicle telemetry
- Integrated avionics and desktop software for programming in labs

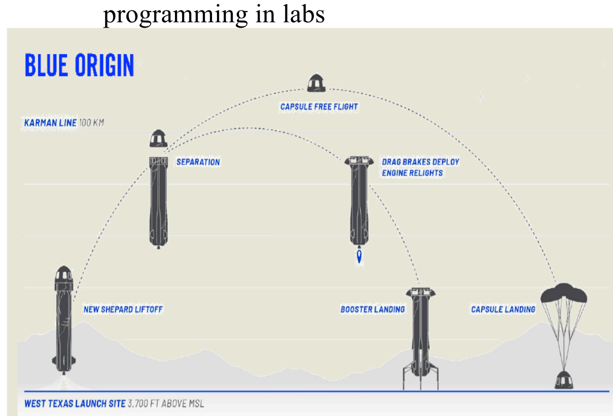

Figure 3: Blue Origin System mission profile

2.3 Dream Chaser

Designed by the American private company Sierra Nevada Corporation, it's a vehicle capable of autonomous landing on runway by gliding. In this is similar to the SpaceShip (even if the last one has two pilots on board); but actually it presents some differences: first of all, it's designed to reach the low Earth orbit (LEO), in particular docking at the ISS. Therefore a greater amount of thrust at launch is required, and the innovative air-launch is replaced by a more regular ground launch, placing the ship in the fairing of the rocket (see Figure 4).

Figure 4: Sierra Nevada Dream Chaser in launch configuration

The Dream Chaser is composed of two modules: the ship itself, the only part that is supposed to re-entry, and a cargo module, anchored to the back of the ship, equipped with solar panels in order to provide current to the payload. Once undocked from the ISS (Figure 5), the ship can perform an automatic re-entry in atmosphere and land without engine. The main goal of this vehicle is to carry supplies to the ISS, in an unmanned configuration. Also, SNC selected United ULA as the launch vehicle provider for the Dream Chaser spacecraft's six NASA missions to the International Space Station. The Dream Chaser will launch aboard ULA's Vulcan Centaur rockets for its cargo resupply and return services to the space station, starting in 2021 [12], .

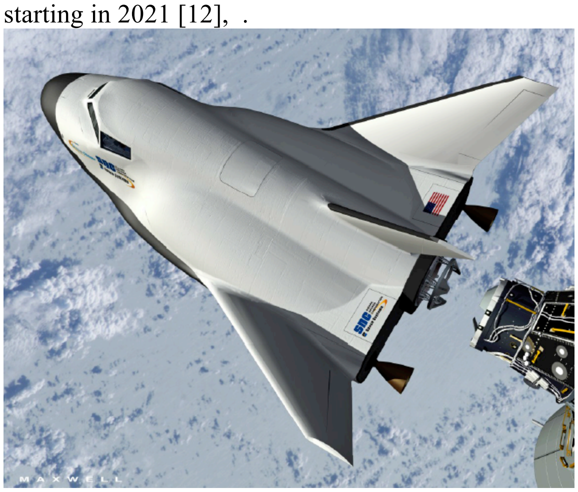

Figure 5: Dream Chaser undocks from ISS

2.4 IXV

IXV was a reentry demonstrator technology vehicle funded by ESA; its mission consisted in verifying the capability of performing an automatic controlled atmospheric re-entry from a suborbital equatorial trajectory up to 400 Km altitude (Figure 6). It was equipped with a guidance, navigation and control system, and a thermal shield made of ceramic material to protect the bottom side and the nose during re-entry.

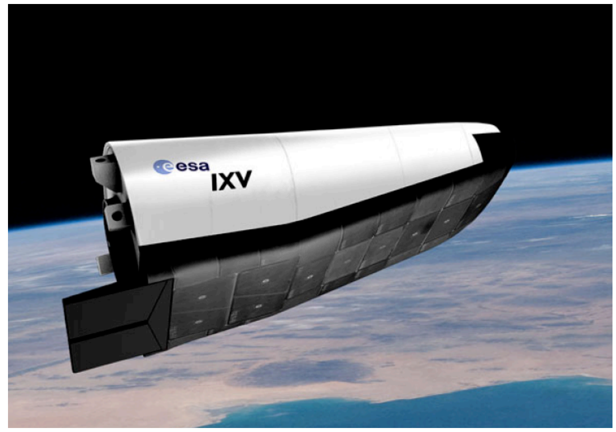

Figure 6: The ESA IXV [Credits: ESA]

IXV was launched in February 2015 by a Vega Rocket and splashed down in the Pacific Ocean after a mission duration of a bit more than 100 minutes. IXV can be considered the first case of suborbital vehicle.
Since it was a technological demonstrator, it didn't carry any scientific payload. Nevertheless it open up the path to future development: in fact its follow on development is the Space Rider System which will be launched by a Vega Rocket and will perform various activities depending on the mission: carrying scientific payload to conduct experiments in microgravity, robotic demonstrator, Earth observation, telecommunication.

2.5 Space Rider

Space Rider (Figure 7) [13] aims to provide Europe with an affordable, independent, reusable end-to-end integrated space transportation system for routine access and return from low orbit. It will transport payloads for an array of applications, orbit altitudes and inclinations. Space Rider is fully integrated with Vega-C to provide a space laboratory for payloads to operate in orbit for a variety of applications in missions lasting about two months. Space Rider will have the potential to allow:

- free-flying applications such as experiments in microgravity;
- in-orbit technology demonstration and validation for applications such as exploration, Earth observation, Earth science, telecommunication, surveillance applications such as Earth disaster monitoring.

Space Rider will be launched on Vega-C from Europe's Spaceport in Kourou, French Guiana, remain in space in a low-drag altitude orbit for about two months, return to land on Earth with its payload, and then be prepared for the next mission. Space Rider is designed to operate at different orbital inclinations, from equatorial to high-latitude. The Azores archipelago is therefore a suitable European landing location for missions that require high-latitude inclinations because it allows Space Rider to return at the same latitude as its operational orbit, requiring fewer deorbiting manoeuvres.


Figure 7: The ESA Space Rider [Credits: ESA]

2.6 Airbus Defence and Space Spaceplane

It is a concept of Spacplane developed in the last decade, similar for some aspects to the Virgin Galactic SpaceShipTwo, in fact it was intended for tourist sub orbital flight, with the possibility of carrying up to 4 tourists with a pilot.The peculiarity of this vehicle is that it's supposed to perform every phase of the mission independently, in fact it's a concept of SSTO, single stage to orbit (Figure 8). It's equipped with 4 turbofan engines per atmospheric propulsion, which let the vehicle to get to 12 km of altitude. At this point we have the ignition of a liquid rocket engine with LOX and Methane, which is the start of a steep ascending phase, exceeding Mach 3, reaching, at the end of a 90 seconds burning, an altitude of 60 km. Afterwards, the vehicle keeps climbing till reaching 100 km, letting weightlessness to be experienced.


Figure 8: Airbus SpacePlane taking off [Credits: Airbus]

The Re-entry phase is conducted at high angle of attack in order for the SpacePlane to dissipate as much velocity as possibile in the atmosphere till getting to 15 km of altitude, where conventional turbofans are re-activated to allow a regular landing like an airline aircraft.

2.7 Skylon

Skylon is a vehicle designed by UK based on reaction engines in partnership with UK Space Agency. It's a SSTO, able to reach LEO. It's equipped with an innovative engine, called SABRE, which works with LOX and liquid hydrogen. The engine is characterized by two operative modes:

- Airbreathing mode: the engine takes air from the outside atmosphere and then strongly compressed, while fuel for combustion (hydrogen) is contained in tanks;
- Rocket mode: once reached an altitude of 26 Km, at Mach 5, this mode is activated; oxygen is no longer taken from the atmosphere but from on board tanks, in order to reach the orbit.

Both take off and landing are horizontal on runway. Currently it's only aimed at payload transportation, but future development expects also to carry up to 40 passengers [14]. Figure 9 shows the Skylon taking off horizontally.


Figure 9: Skylon taking off [Credits: UK BRE and UK Space Agency]

2.8 Space Liner

Space Liner a DLR project, currently stopped for lack of funds. It's a concept of a point-to-point tourists transport, alternatively a cargo transport vehicle for LEO. In both cases, it's reusable.

It consists in two stages, with a vertical take off and horizontal landing, with the presence of a booster for launch phase connected to the actual spaceplane, able to accommodate up to 50 passengers, with two pilots.Propulsion system consists in 11 liquid rocket engines (9 for the booster while 2 for the ship), which use LOX and liquid hydrogen. After an initial ascending phase and booster separation, spaceplane engines shutdown occurs, at an altitude of 80 Km. At this point the ship can glide over very long distances, reaching a speed of many Mach numbers. Maximum loads of acceleration occur during the propulsive phase, without exceeding 2,5 g. Figure 10 shows the Spaceliner separating from boosters.

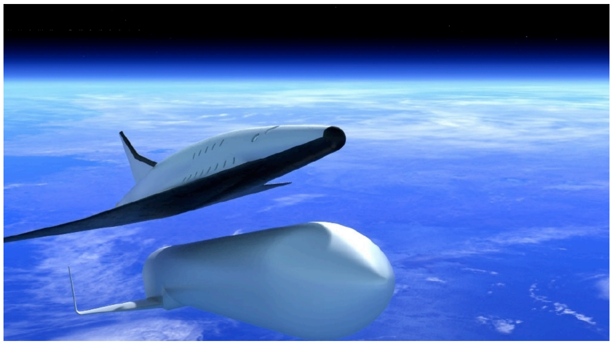

Figure 10: Spaceliner detachment from booster [Credits: German Space Agency]

2.9 Boeing X-37

It's an unmanned vehicle initially developed by NASA. Then the project moved to the Defence Department and the vehicle now operated by USAF in partnership with NASA.

Figure 11: Boeing X-37 during descending [Credits: Boeing]

The vehicle has already performed five long-duration missions in LEO, being used as a technological demonstrator. For the ascending phase, it utilises a launch vehicle (Atlas V, Falcon 9), of which it constitutes the payload. It can re-enter independently landing on a runway. Figure 11 shows the X37 during descending phase.

2.10 HAPS

High-altitude platforms or High-Altitude Pseudo-Satellites (HAPS) are, according to Article 1.66A of the InternationalTelecommunication Union´s (ITU) ITU Radio Regulations (RR), defined as "a station on an object at an altitude of 20 to 50 km and at a specified, nominal, fixed point relative to the Earth". Usualy, HAPS feature the following characteristics:

- Permanent coverage in a stationary area;
- Operations in full autonomy because powered by solar energy;
- Offer simultaneous combinations of different services;
- Network with other platforms including satellites or drones;
- Can be moved where services are requested;
- Can be reconfigured to accommodate different kind of payloads;

The main services provided by HAPS include Surveillance, Environmental Monitoring, Navigation, Telecommunication. Some defense services may also be provided. HAPS can be considered a complement or extention of satellites capabilities, ground infrastructures and opportunity to develop new services. Thales Alenia Space is developing the Stratobus platform (Figure 12), an autonomous, multi-mission stratospheric airship, midway between a drone and a satellite. Stratobus is considered part of the HAPS [High Altitude Pseudo Satellite] family. Stratobus operates at an altitude of 20 kilometers and is designed for a wide range of civil or military regional applications: telecommunications, navigation, observation (especially surveillance).

Figure 12: Pictorial sketch of Stratobus (credits Thales Alenia Space)

Table 1 is a comparison of the different approaches for commercial access to space described above.

Table 1: Summary of main technologies for access to space

Spaceplane	Flight	Mission	Take off	Landing	Status	Propulsion
SpaceShipTwo	Suborbital	Commercial Tourist	Airlaunch (Carrier)	Horizontal on Runway	Test	Hybrid (HTPB/N2O)
Dream Chaser	Orbital (LEO)	Payload & Crew to ISS	Vertical (Launcher)	Horizontal on Runway	Test	Liquid (Propane/N2O)
IXV	Orbital (LEO)	Tech. Demonstrator	Vertical (Vega)	Splash – Down	Flown in 2015	Liquid (Hydrazine)
ADSS	Suborbital	Commercial Tourist	Horizontal (SSTO)	Horizontal on Runway	Concept	TF + Liquid (LOX/Methane)
XCOR Lynx	Suborbital	Com. Tourist & Payload	Horizontal (SSTO)	Horizontal on Runway	Concept	Liquid (LOX//Kerosene)
Skylon	Orbital (LEO)	Com. Tourist & Payload	Horizontal (SSTO)	Horizontal on Runway	Concept	SABRE
Space Liner	SO (Point to Point)	Commercial Tourist	Vertical (Launcher)	Horizontal on Runway	Concept	Liquid (LOX/Liquid H2)
Boeing X-37	Orbital (LEO)	Tech. Demonstrator	Vertical (Launcher)	Horizontal on Runway	5 missions	Hypergolic Nitrogen-Tetroxide/Hydrazine
SOAR	SO & LEO	Payload	Airlaunch (A300)	Horizontal on Runway	Concept	Liquid (LOX/Liquid H2)

It can be observed that different takeoff approaches are being considered, in particular the air launched spaceflight system from Virgin Galactic and the vertical launch from Blue Origin. These technologies consider at least two stages, while the promising SSTO Skylon is currently under test.

3. Mission tradeoff elements: the case of suborbital flight

This section provides some guidelines that can be used to make an informed decision on which mission approach is the most suitable to reach a defined objective. The starting point is a comprehensive definition of the misson statement that in case of suborbital flight and based on proper market analysis can be written as: *Take untrained people (tourists) into suborbital flight to let them experience and enjoy few minutes in microgravity. Alternatively provide opportunities for microgravity experimentation. This shall be accomplished by a spaceplane, with one or more stages, able to land safely on a runway.*

Assuming horizontal landing as per mission statement, the takeoff options to be traded off include:

- SSTO with only one stage which is the spaceplane itself;
- Vertical Launcher;
- Air launch featuring the spaceplane air lifted and released by a carrier aircraft;

The tradeoff process is based on the definition of suitable Figures of Merit (FoM), that are specific parameters to be quantified and to be used as reference for comparing the different alternatives to be traded off [6]. Typical FoM are Safety, Cost and Complexity, as indicated in Figure 13.

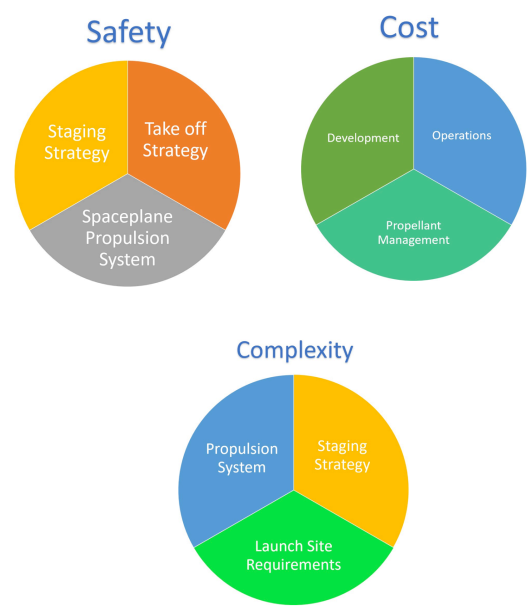

Figure 13: Figures of Merit used in the mission concepts tradeoff

Takeoff strategy, captive on top/bottom strategies, propulsion strategy and used propellants have been taken into consideration. The tradeoff has determined that air launch is the most suitable strategy to fulfill the above defined mission statement. For example, Figure 14 shows the main advantages and drawbacks associated with the selected option with reference to takeoff strategy.

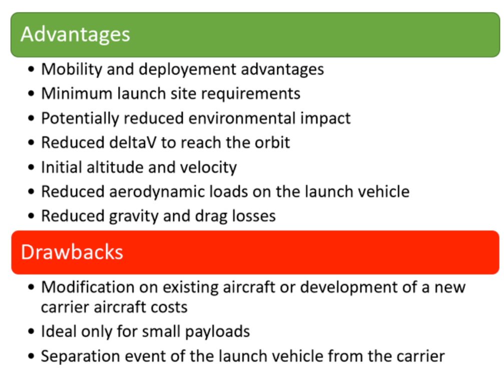

Figure 14: Air Launch Advantages and Drawbacks

The evaluation of the figures of merit was conducted by using a mathematical model based on specific weighting factors that show the impact of the propulsive system and propellant system on Safety, Complexity and Cost, as shown in Table 2.

Table 2: Weighting factors for each FoM

	SSTO	Launcher	Carrier
Safety	Ke = 0,75	Ke1 = 0,75	Ke1 = 0,5
	Kt1 = 0,75	Ke2 = 0,25	Ke2 = 0,75
		Kt1 = 0,5	Kt1 = 0,33
Cost	Ke = 0,75	Ke = 0,5	Ke = 0,25
	Kt = 0,75	Kt = 0,5	Kt = 0,25
Complexity	Ke = 0,75	Ke = 0,75	Ke = 0,25
	Kt1 = 0,75	Kt1 = 0,75	Kt1 = 0,25
	Kt2 = 0	Kt2 = 0	Kt2 = 0

Bottomline of the process is the calculation of the tradeoff indexes for every configuration and the result is shown in Table 3.

Table 3: Tradeoff indexes for different cases

	K1	K2	K3	SSTO	Launcher	Carrier
Case 1	0,33	0,33	0,33	0,20	0,480	0,485
Case 2	0,5	0,25	0,25	0,40	0,960	0,970
Case 3	0,25	0,5	0,25	0,1330	0,3158	0,3233
Case 4	0,25	0,25	0,5	0,1330	0,3243	0,3233

It is possible to see that the best configuration is the Air Launch with Carrier and Spaceplane, which is the one selected by Virgin Galactic. Primary importance is given to Safety, while complexity is less concerning since in the carrier configuration a relatively simple propulsion and propellant systems are used. If primary emphasys is on the cost, then the vertical launch solution is a better fit, due to already existing and consolidated technologies available.

4. Trajectories Simulations

Considering the findings of the previous section where an Air Launched Spaceflight System has been identified as the preferred option for fulfilling a suborbital flight mission statement, a proper trajectory modeling has been performed considering as a reference the Virgin Galactic SpaceShipTwo and WhiteKnightTwo. In particular, two different missions have been considered, one aimed at space tourism and the second aimed at microgravity experimentation [15]. The main difference is that the touristic mission will achieve minor altitude such to be less stressfull for passengers in terms of flight loads. The scientific mission will achieve a higher altitude and a longer microgravity period to allow more time for experimentation and testing. The approach to the trajectory simulation mathematical model is based on the rigid body model and point like mass model [7] that takes into account aerodynamic forces, in terms of drag and lift, gravity force, considering a flat-Earth reference frame, thrust force, given by the propulsion system, mass loss, due to the aircraft fuel consumption. Special care was also given to properly modeling the thrust, the aerodynamic forces and the air density. The numerical methodology is based on implementation of the fourth order Runge-Kutta method (RK4) to integrate the physical equations. The Runge-Kutta methods are a family of explicit or implicit iterative methods used in temporal discretization for approximating solutions of ordinary differential equations.

The outcome of the simulation both for a tourist and scientific suborbital flights has been achieved assuming appropriate values for performance and geometry parameters: trajectory obtained is a good approximation of real models. For a tourist mission the following values are assumed (Table 4) and the resulting trajectory is shown in Figure 15:

Table 4: Suborbital tourist mission data

Tourist Mission Profile	
Mass	13000 Kg
Release Altitude	15200 m
Carrier velocity at release	128,61 m/s
Release duration	6 s
Burn duration	60 s
Maximum value of thrust	378 kN
Minimum value of thrust	222 kN
Fuel mass	6800 kg
Apogee	103,70 Km
Perc. of Maximum Thrust	80%

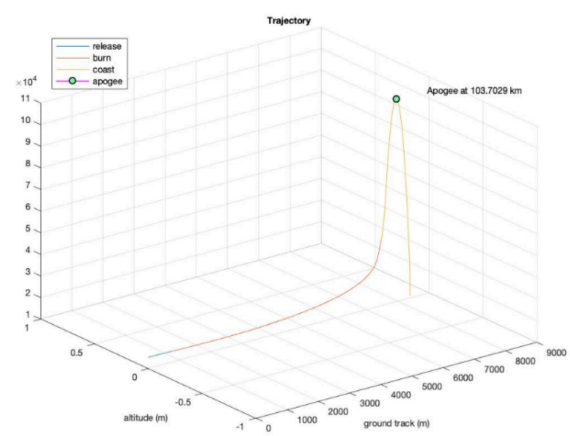

Figure 15: Suborbital tourist mission profile

For a scientific mission the only difference is the percentage of maximum thrust used during the burning phase, in order to get to an higher altitude and take advantage of a longer time in microgravity; the relevant data table and trajectory profile are shown in Table 5 and Figure 16 respectively.

Table 5: Suborbital scientific mission data

Scientific Mission Profile	
Mass	13000 Kg
Release Altitude	15200 m
Carrier velocity at release	128,61 m/s
Release duration	6 s
Burn duration	60 s
Maximum value of thrust	378 kN
Minimum value of thrust	222 kN
Fuel mass	6800 kg
Apogee	127,49 Km
Perc. of Maximum Thrust	90%

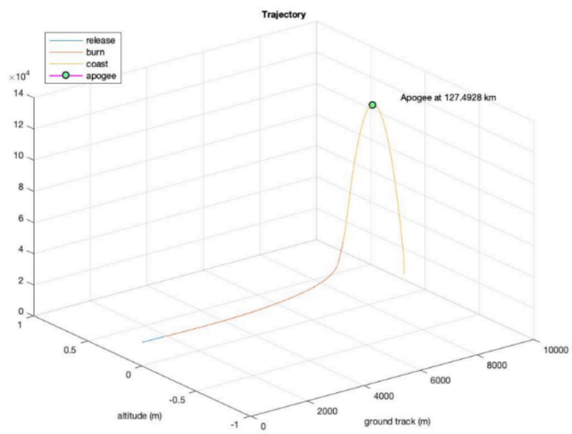

Figure 16: Suborbital scientific mission profile

5. Spaceport and Infrastructures

5.1 Operating Cycle

The designated Spaceport for the specific suborbital spaceflight system has to make available the appropriate capabilities and infrastructures to properly support the entire operating cycle, in particular considering the reusability of the system to match the expected market demand. The end-to-end operating cycle of a suborbital spaceflight system [15] is described in Figure 17.

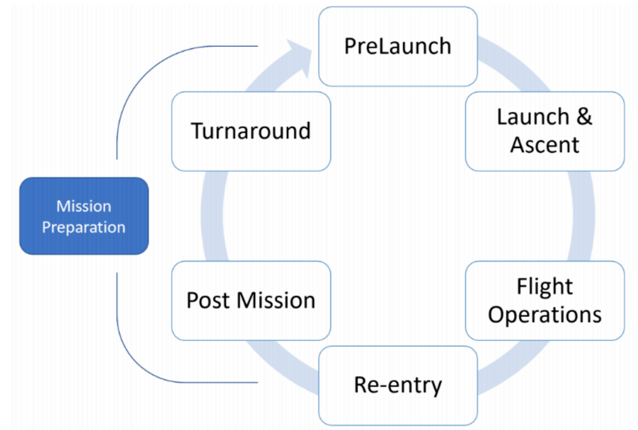

Figure 17: End to end operating cycle

A description of the main phases is herein provided:

The Mission Preparation phase can be considered as the first part of the mission and includes:

• Postflight inspection and checkout (from previous flight)
• Vehicle configuration preparation, either tourist or scientific;
• Payload preparation and integration;
• Ground segment configuration preparation;
• Crew and ground personnel training (including nominal and contingency missions simulation) as well as passengers;
• Completion of process verification and certification for flight readiness;
• Execution of Functional tests

The Pre Launch phase includes:
• All the activities required to prepare the vehicle and the ground segment for flight;
• A preflight checkout to verify the correct behaviour of all the subsystems and equipment (for flight and for ground as well);
• Preflight runway operations;
• Vehicle fuelling;
• Depending on the mission, either scientific or tourist, experiments have to be installed or passengers boarded, as well as crew members.

Launch-Ascent operations consists of:
• Acquisition and assessment of external condition and weather condition to allow go for launch within the system performances and safety constraints;
• Continuous monitoring of the vehicle telemetry before and during launch, as well as during ascent, in order to assess performances and safety conditions;
• Continuous tracking of the vehicle;
• Monitoring crew/flight participants conditions and continuous voice coordination with the crew;

Flight Operations phase follows the shutdown of the rockets with subsequent start of the ballistic part of the flight; it includes:

• Continuous monitoring of the telemetry to assess the status of the vehicle;
• Continuous tracking and monitoring of the trajectory and its propagationfor re-entry assessment;
• For a scientific mission: experiment execution and relative telemetry acquisition, monitoring and control;
• Passengers microgravity experience, monitoring of passengers and crew conditions.

Reentry operations includes:
• Continuous monitoring of the telemetry to assess the status of the vehicle;
• Continuous assessment and forecast of the vehicle trajectory, also in case of planned controlled re-entry abort;
• After landing, perform vehicle inspections and safing;
• Continuous support to the crew and passengers during disembarking.

Post Mission Operations include:
• Transportation of the vehicle in the turn-around area;
• Storage and consolidation of the collected data;
• For scientific flight: experiment removal from the vehicle;
• Download crew and passengers items;
• Mission performance assessment.

The turnaround phase consists of:
• Vehicle physical inspection;
• Maintenance activities execution;
• Vehicle specific checkout;
• Replacement and retest of critical components (as landing pad and propulsion system)
• Final preparation for next flight.

5.2 Spaceport

The methodology to assess a suitable airport is based on a specific set of requirements [16] and then to evaluate how the airport meets those requirements, as well as what may need to be improved. The initial evaluation is based on a horizontal take off and landing suborbital space flight system, but it is expected that the Spaceport shall have to adapt to support different applications such as allow landing of orbital platforms, satellite air launch or act as a Stratoport for HALTA platforms. The main requirements fall in the following categories (Figure 18):

• Airport area and surroundings (territory and population density);
• Airport Configuration (runway length and altitude);
• Climate and weather conditions (clouds, wind, rain);
• Socio demographics: these are qualitative variables in nature but can be significant to achieve final determinations. For instance the presence of aerospace districts, the subsidiary activities, network of suppliers, transport and communication, international airports vicinity/accessibility and tourist attraction availability.

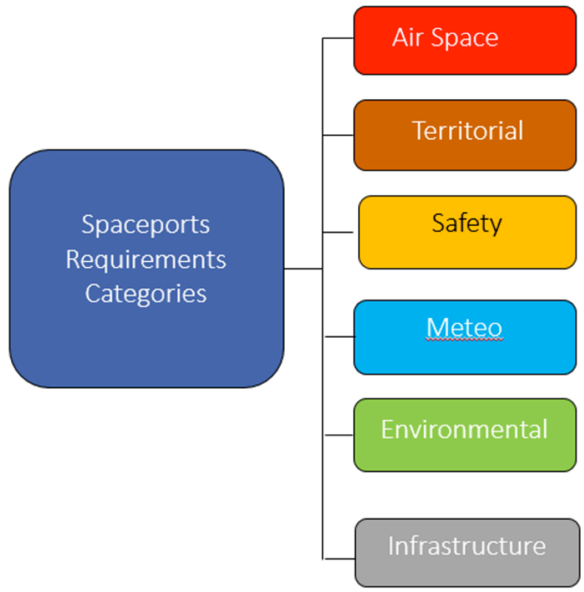

Figure 18: Spaceport Requirements Categories

Territorial requirements
- Spaceport has to be located in a low aerial traffic site in the area that also includes the spaceplane release from the carrier.
- Spaceport has to be located in a low residential site in the area between the spaceplane release from the Carrier and the runaway.
- Spaceport area has to undergo an environmental impact assessment coordinated with local authorities.

Configuration and area requirements
- Runway minimum length (3000 meters) and altitude above sea level;
- Availability of He and N2O refuelling system at the Spaceport premises;
- N2O refuelling and depot area safe distance;
- Hangar dimensions;
- Runway availability for suborbital operations;
- Spaceport has to feature facilities for crew, passengers and ground support equipment;
- Spaceport shall accommodate suborbital spaceflight simulators;

- Communication frequencies assigment has to be agreed with the Air Traffic Control Authority;
- Proper security procedures have to be put in place to fulfil ITAR requirements;

Climatic Conditions requirements

- Altitude of the lowest cloud system (Ceiling) during VFR approach and landing operations of the vehicle permitted by the Spaceport
- Spaceport has to enable Instrumental Flight Rules with a Category 1 ILS
- Allowed crosswind velocity at Spaceport premises
- Maximum Wind Velocity at ground
- Maximum Wind Velocity at the proper altitude
- Maximum Wind Shear at the proper altitude
- Spaceport location has to minimize fog conditions

Airspace

- Flight operations have to take place at a proper distance f rom airways
- Spaceplane release from Carrier vehicle has to take place in a segregated area without need to fly in IFR mode

5.3 The Ground Station

The Ground station provides space to ground communication with the spaceplane. The Ground Station selection process in terms of both technical specifications and positioning at the Spaceport largely depends on the suborbital flight trajectory with the goal of providing trajectory tracking and receival of vehicle telemetry during the entire mission. Usually only one Ground Station is sufficient to the purpose even if future technology evolutions like point to point, antipodal commercial flight will certainly require a network of multiple Ground Stations. Further, an important aspect to be evaluated in the presence of physical obstacles that can be detrimental to the Ground Station performance, in particular at low elevation angles. Generally studying spacecraft trajectory it's possible to determine the required coverage angle which allows communication between the vehicle and the ground station. For example, for a satellite on orbit around the Earth, the scheme can be: In particular coverage angle depends on spacecraft altitude and elevation angle, according to Figure 19, in which different curves are obtained varying the altitude and the elevation angle (between 5 and 30 degrees): In order to have elevated visibility time an high altitude is desirable; but this is applicable for a spacecraft on orbit. For a suborbital flight we expect low altitudes, while for elevation angle it could range between low and high values depending on the position of the spaceplane during the various phases of the mission with respect to the ground station.

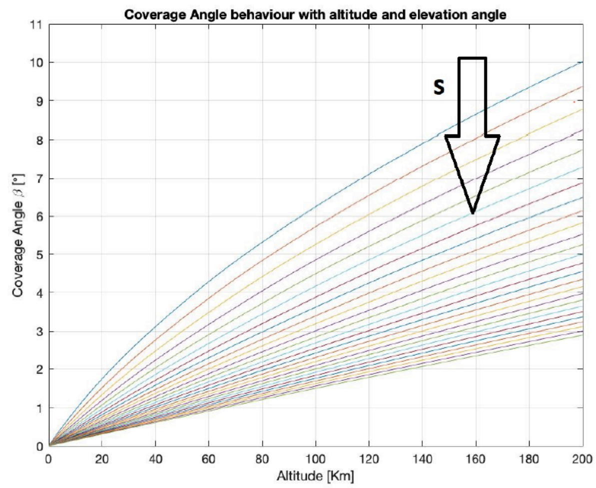

Figure 19: Coverage angle vs altitude and elevation angle

For commercial applications, a Spaceport should feature augmented Ground Station capabilities [17], [18] with respect to only supporting suborbital flight needs. A typical Ground Station should also include suitable capabilities of tracking and operating specific flight segments and in particular Low Earth Orbit (LEO) small Satellites, cubesats and orbital reentry vehicles, acquiring the relevant telemetry and storing it for post mission processing. The Ground Station should operate in S (2-4 GHz), X (7-11GHz) bands. The possibility to extend download capability to KA (26.5-40 GHz) Band will also be evaluated. The Ground Station shall have downlink capability in all these bands and uplink capability on S band. This Ground Station is also required to fit within the low cost nanosatellite framework while providing support for multiple missions. In fact, to meet this requirements, the ground station is designed to be modular so that future upgrades would have minimal impact on the other subsystems. The Ground station consists of a antenna dish, a set of R/F sources, an XY positioner and equipment necessary for receiving, transmitting and recording data (including a GPS receiver for location and time synchronization of the station). The equipment will be integrated into racks and is completely controllable via station-supervising workstations. The Ground Station shall also feature an Operation Centre to properly perform the relevant activities. The Operation Centre includes all the equipment needed to perform the required mission operations for the designated vehicle or satellite. In particular, proper displays will be available for performing the telemetry monitoring functions and manage the Ground Station operations. The Ground Station shall feature proper supervision capability to provide controlling and monitoring of the entire station, including configuration of equipment, automatic testing of system performance, event recording, antenna positions and information related to tracking during a pass. This supervision ensures automatic recovery of orbital information (e.g. from a server or from websites), controlling and organizing the timetable of satellite passes (application of defined priorities, calculating pointing data for the Program Track mode.)

An example of Ground Station Architecture including all subsystems and possible hardware configuration is shown in Figure 20.

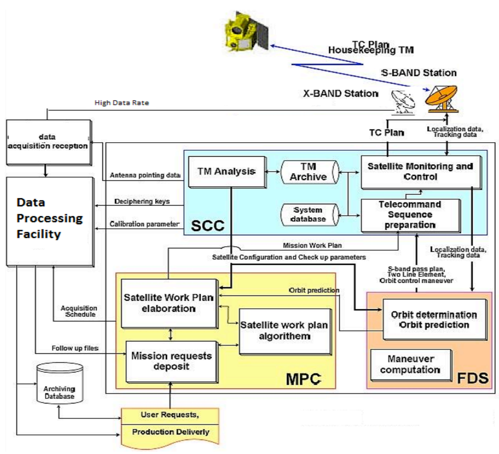

Figure 20: Example of Ground Station Architecture

The high rate received data can be stored and distributed through a dedicated recording system. The station can be operated manually via a user-friendly man-machine interface or in fully automated mode, with the possibility of remote monitoring and maintenance. The main Ground Station subsystems including antenna are shown in Figure 21.

Figure 21: Ground Station Subsystems

5. Economic and organizational aspects

The present section addresses general organizational aspects in support to the development of sustainable commercial spaceflight initiatives evolving in the new space economy market; it is evident that growing communities of users have a need for microgravity access for multiple applications and this not only involves the commercial suborbital spaceflight [19], but other platforms like nano satellites for different applications, orbital services to payloads, or stratospheric platforms. It is now necessary to bring these parties together through the setup of specific service and organizational model aimed at providing to the users a turn-key service to offer access to a wide range of platforms and provide the best match end-to-end package of services for their Payloads & experiments; such services cover each key step of the process, from initial interactions to evaluation of the user's needs, selection of the most appropriate platform, ground and flight operations, retrieval operations, thus allowing faster and easier way to access and exploit microgravity. Further, the new space economy is strongly focused on the upstream and downstream segments [20]. The upstream segment includes all activities that focus on the design, manufacture, assembly, launch, functioning, maintenance, monitoring and repair of spacecraft to be sent out to space as well as the products and services related to them; the downstream segment refers to all activities that employ data and knowledge that are derived from the space for Earth-related objectives as well as the products and services that support them. The upstream segment can be seen as the provision of space technology, whereas the downstream segment can be seen as the exploitation of space technology.

Typical users include scientific institutions, industry, public institutions and private people. In detail, the following services may be included:

- Assessment of experiment and client requirements to determine the best match;
- Logistics services to transport the experimental payload to/from the Spaceport;
- Integration services to ensure the payload can operate as expected aboard the selected platform;
- Contractual services to ensure all legal, regulatory are fully met:
- Consultation services to tailor current and future client needs to specific flight services.

In order to develop sustainable commercial spaceflight initiatives, once the Main Spaceport Tenant (which can be identified as the end–to-end service provider) identifies the suitable platform based upon the relevant user needs, it is necessary to determine the

Operations/Services (O/S) and related delivering organizations (suppliers, contractors). In fact, in the new space economy the O/S market evolution is calling for a new articulation of delivering organizations ranging between hierarchy (O/S performed by the main spaceport tenant) and pure market (O/S delivered by a supplier/contractor). Operations/Services (O/S) are technically identified when needs and platform are known. Then, the nature of the O/S has an impact on how all the stakeholders involved at the spaceport level are organized.

Further, the nature of the O/S has an impact in the organizational choice of all the stakeholders involved at the spaceport level. To analyse these aspects, the nature of the O/S has to be examined from the point of view of the involved transaction cost (economics), in order to evaluate the most appropriate organization and relationship between demanding and supplying organizations. The following considerations are based on the Theory of Transaction Costs [21] that provides the proper background in determining when activities would occur within the market and when they would occur within the enterprise. More specifically, transaction cost theory predicts when the governance forms of hierarchies, markets, or hybrids (e.g., alliances) will be used; in particular, when transaction governance costs are high, internalizing the transaction within a hierarchy is the appropriate decision. Conversely, when transaction governance costs are low, buying the good or service on the market was the preferred option.

Three dimensions were developed for characterizing transactions: frequency, uncertainty (technological and commercial) of the delivered operation/service, asset specificity involved in the transaction. With reference to the operating cycle described in Subsection 5.1, if we restrict the evaluation to the suborbital flight, with reference in particular to the Virgin Galactic suborbital spaceflight system operations, an initial assessment is shown in Table 6, where the delivered operations/services are associated with the corresponding type of dimension and the key involved stakeholders.

Table 6: Example of transaction type and stakeholders for suborbital spaceflight mission processing

Delivered operations/services	**Type of transaction**			**Key stakeholders involved**	**Delivering organization**
	Frequency	Uncertainty	Specific Asset required		
Postflight inspection and checkout (from previous flight)	Once per week	Moderate	Ground Support Equipment, Hangars, Tools	Main Spaceport Tenant, Spaceport owner	Ground Operations Provider, vehicle manufacturer
Vehicle configuration preparation, either tourist or scientific	Once per week	Moderate	Ground Support Equipment, Hangars, Tools	Main Spaceport Tenant, Spaceport owner, Payload developer	Ground Operations Provider, vehicle manufacturer
Payload preparation and integration	Once every quarter	Low	Payload Processing Labs	Main Spaceport Tenant, Spaceport owner, Payload developer	Ground Operations Provider, Payload developer
Ground segment configuration preparation	Once per week	Low	Standard tools and equipment	Main Spaceport Tenant, Spaceport owner	Ground Operations Provider
Crew and ground personnel training (including nominal and contingency missions simulation) as well as passengers	Once per week for crew, twice per year for operators	Moderate	Simulators, trainingware	Main Spaceport Tenant, Spaceport owner	Ground Operations Provider, Trainers
Completion of process verification and certification for flight readiness	Once per week (TBC)	Moderate	Regulatory documentation, flight and ground operations procedures	Civil Aviation Authority, Spaceport Owner, Spaceport Main tenant, Safety Officer	Ground Operations Provider, vehicle manufacturer
Execution of Functional tests	Once per week	Moderate	Ground Support Equipment, Hangars, Tools	Main Spaceport Tenant, Spaceport owner	Ground Operations Provider, vehicle manufacturer

Using this approach, O/S should be internalized (hierarchy) when low frequency, high uncertainty, and highly specific assets occur for the transaction. On the contrary, O/S that has to be externalized by the main spaceport tenant can be recognized, corresponding to the market organization model. Types of transaction in between the two extreme cases (hierarchy or market) require hybrid organizational models where agreement with different level of partnership (i.e., alliance, consortium) has to be designed between main spaceport tenant and the delivering organization.

The approach also suggests who is better to take in charge the investment as high asset specificity call for public investments (and organization) in order to avoid opportunistic behavior and market failure.

6. Future applications

A spaceport shall be regarded as an asset open to future technology evolutions; in particular, future generation transportation system [22] able to transport cargo and passengers between different points on Earth at a much reduced transfer time is attracting more interest and is triggering several studies. The evolution of the suborbital flight to a point to point requires accurate studies focused of different aspects like aerothermodynamics, thermal protection and propulsion systems. Moreover in the future a single Spaceport may evolve into a network of Spaceports that act like airports. According to UBS estimations, the point-to-point market prediction is around $ 20 Bln by 2030 competing with long distance airline flight. For sure key success factor for the development of point-to-point suborbital transportation is the availability of a network of properly featured Spaceports to allow the operations preparation and execution, a proper harmonized regulatory framework and of course cost competitiveness. Other future application regards the satellites air launch, which consists of a carrier aircraft that transports and releases at about 15.000 meters of altitude a totally expandable multi-stage small launcher featuring the satellite to be placed on orbit. Depending of the specific system, the launch can occurin the speed range Mach 0.8-1.2. Even though the Spaceport requirements for suborbital flight still fit the satellite air launch operations scenario, specific facilities have to be considered such as launcher and payload assembly and integration and propellant loading provisions. The concept of a multi functional spaceport has to include such functionalities.

7. Conclusions

The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section.

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